Heat transfer and thermally induced stresses in window glass coated with optically active nano-particles

A thesis presented for the degree of
Masters in Engineering

By

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Declaration of original authorship

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that I am the primary and original author of this thesis, and any help I have received in my research work and its preparation has been acknowledged. In addition, I certify that all literature sources are cited and listed in the references of this thesis.

19/6/07

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Humayer Ahmed CHOWDHURY Date

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Symbol Index - Nomenclature

English Letters	
A	Area of the glass, m^2
c_p	Specific heat
$D_{r,\theta}$	Diffusely emitted radiation as a function of distance, r and angle, θ
$D_{0,0}$	Surface intensity of radiation reflected perpendicularly from glass surface
E	Modulus of elasticity (Young Modulus)
E_λ	Spectral irradiance of the light source, $W.m^{-2}.nm^{-1}$, as $f(\lambda)$
F	Proportion of incident radiant energy transferred to the interior of the glass
Gr_{L-}	Grashof number
h	Convective heat transfer coefficient, $W.m^{-2}.K^{-1}$
I_λ	Maximum specular reflectance
k	Thermal conductivity $W.m^{-1}.K^{-1}$
K_c	Stress intensity
l_0	Length at 273K
l_t	Length at temperature t
l	Mode of the resonance (l=1 produces a dipole resonance, l=2 a quadrupole resonance, l=3 a octupole resonance)
L	Height of the glass pane, m
m	Parameter accounting for decrease in $D_{r,\theta}$ as $f(r)$
n	Specular reflection exponent in Phong's Law
Nu_L	Nusselt number
Pr	Prandtl number
q	Heat transfer through or from glass surface, W
q_c	Convected heat energy
q_i	Incident heat energy
q_r	Heat energy radiated
Ra	Rayleigh number

R_{sol}	Proportion of the total solar irradiance that is reflected
T_o	Outside temperature
T_i	Inside temperature
T_{air}	Temperature of laboratory air, K
T_f	Film temperature K
T_{s}	Temperature of the glass surface, K
T_{vis}	Proportion of visible spectrum that is directly transmitted by glass
T_{sol}	Proportion of the total solar irradiance that is transmitted
T_λ	Total spectral transmissivity of the glass, as $f(\lambda)$
V_λ	Photo-optic luminous efficiency function of the human eye, as $f(\lambda)$
x	Ratio of the inner and outer radii of a nano-shell particle
Greek Symbols	
α	Thermal expansion co-efficient 1/°C
β	Volumetric coefficient of thermal expansion 1/°C
ϵ	Emissivity
γ	Angular deviation from specular reflection
v	Poisson's ratio
ρ	Density kg/m^3
$\varepsilon'_{Au}(\lambda)$	Real part of the dielectric constant of gold, as f(λ)
$\varepsilon'_{m}(\lambda)$	Real part of the effective dielectric constant of the matrix surrounding the gold nanoparticle, as f(λ)
θ	Angle between axis of radiation sensor and surface of glass
λ	Wavelength of light, nm
$\sigma_{thermal}$	Thermal stress
ϕ	Volume fraction of gold particles lying on the surface of the glass
ω_{l-}	Energy of symmetrically coupled plasmons on the inner and outer surfaces of the metal shell, eV
ω_s	Surface plasmon energy of a solid nanoparticle, eV
Subscripts	
a	Quantities associated with air
b, back	Back face of the glass
conv	Convective quantities

f	Front face of the glass
rad	Radiation quantities
solar	Solar quantities
Acronyms and abbreviations	
ASTM	American Society for Testing and Materials
ADF_t	Angular Distribution Function of transmittance
ADF_r	Angular Distribution Function of transmittance
CIE	International Commission on Illumination
E971	Standard Practice for Calculation of Photometric Transmittance and Reflectance of Materials to Solar Radiation.
FEA	Finite Element Analysis
G159	Standard Tables for References Solar Spectral
H_t	Haze parameters of transmission
H_r	Haze parameters of reflectance
ISO	International Organisation for Standardization
Kc	Fracture toughness
POB	Probability of Breakage
$Q_{convected}$	Energy convicted
R_{dif}	Diffusively reflectance of energy
R_{tot}	Total energy reflectance
SC	Shading Coefficient
SL	Solar Load
SHGC	Solar Heat Gain Coefficient
T_{dif}	Diffusively transmittance energy
T_{tot}	Total energy transmittance
TOMS	Tetraalkoxysilanes
TiO_2	Titanium dioxide
TSF	Thermal Stress Factor
U	Total heat transfer coefficient

Abstract

Reflective or absorptive coatings for solar control on windows are popular in the architectural and automotive industries. In general, noble metal coatings have been used in reflective applications, and various heat-absorbing dielectric compounds in absorptive ones. The ultimate objective is to moderate incoming infra-red radiation while simultaneously preserving the desirable transparent nature of the window. In addition, one problem with merely absorbing infra-red radiation by the glazing system is that the coating and hence the surface of the special glass becomes very hot. This increased glass temperature will result in thermal stresses leading to an expansion of the glass, which, if not matched by an expansion of the window frame, can cause buckling and cracking. The objective of this project has been to study heat transfer from and through glass surfaces to which IR-screening surface coatings have been applied, and to model the distribution of the resulting thermally-induced stresses in the glass.

The use of coatings of gold nano-particles in an absorptive role has hardly been considered previously. The present study explores the characteristics of such coatings by subjecting panes of various experimental and commercially available glasses to illumination by an array of incandescent lamps at 500 W/m^2, which is a representative figure for a vertical east- or west-facing window in Sydney, Australia or Houston, USA, during March and September. The heat transfer through the samples was determined and used to guide the subsequent finite element analysis. This provided an indication of the thermally induced stresses developed on the glass surfaces due to heat released by the absorptive coatings.